

Superconductivity versus bound-state formation in a two-band superconductor with small Fermi energy: Applications to Fe pnictides/chalcogenides and doped SrTiO₃

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Abstract

© 2016 American Physical Society. We analyze the interplay between superconductivity and the formation of bound pairs of fermions (BCS-BEC crossover) in a 2D model of interacting fermions with small Fermi energy E_F and weak attractive interaction, which extends to energies well above E_F . The 2D case is special because a two-particle bound state forms at arbitrary weak interaction, and already at weak coupling, one has to distinguish between the bound-state formation and superconductivity. We briefly review the situation in the one-band model and then consider two different two-band models: one with one hole band and one electron band and another with two hole or two electron bands. In each case, we obtain the bound-state energy $2E_0$ for two fermions in a vacuum and solve the set of coupled equations for the pairing gaps and the chemical potentials to obtain the onset temperature of the pairing T_{ins} and the quasiparticle dispersion at $T=0$. We then compute the superfluid stiffness $\rho_s(T=0)$ and obtain the actual T_c . For definiteness, we set E_F in one band to be near zero and consider different ratios of E_0 and E_F in the other band. We show that at $E_F \ll E_0$, the behavior of both two-band models is BCS-like in the sense that $T_c \approx T_{ins}$, E_F and $\Delta \sim T_c$. At $E_F \sim E_0$, the two models behave differently: in the model with two hole/two electron bands, $T_{ins} \sim E_0/\ln E_0 E_F$, $\Delta \sim (E_0 E_F)^{1/2}$, and $T_c \sim E_F$, like in the one-band model. In between T_{ins} and T_c , the system displays a preformed pair behavior. In the model with one hole and one electron bands, T_c remains of order T_{ins} , and both remain finite at $E_F=0$ and of the order of E_0 . The preformed pair behavior still does exist in this model because T_c is numerically smaller than T_{ins} . For both models, we reexpress T_{ins} in terms of the fully renormalized two-particle scattering amplitude by extending to the two-band case (the method pioneered by Gorkov and Melik-Barkhudarov back in 1961). We apply our results for the model with a hole and an electron band to Fe pnictides and Fe chalcogenides in which a superconducting gap has been detected on the bands that do not cross the Fermi level, and to FeSe, in which the superconducting gap is comparable to the Fermi energy. We apply the results for the model with two electron bands to Nb-doped SrTiO₃ and argue that our theory explains the rapid increase of T_c when both bands start crossing the Fermi level.

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